Soil Organic Carbon as an Expression of Sustainability in Conservation Agricultural Systems.

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Agriculture depends upon soil to serve as a medium for plant growth, as a reservoir of nutrients and water, and as a filter to detoxify chemical inputs. Soil of high quality contributes to the production of abundant, high quality food, feed, fiber, and fuel. Unfortunately though, poor management can exhaust soil, thereby contributing to land degradation, environmental pollution, and collapse of human civilizations. The development of no-tillage (NT) cropping strategies that mimic natural ecosystems by preserving surface soil organic matter has been a relatively recent development in human history, but may become an enormously important development to reverse the widespread degradation of land that is occurring around the world today (Lal et al., 2007).

1. Soil organic matter and its relationship to soil functions

Organic matter is generally a small, but critical component of productive and high quality soil. Since about 58% of soil organic matter is composed of carbon (C), scientists prefer to talk about this organic component as soil organic C - a straightforward and quantitatively practical property to determine. Typically, organic C is <10% of the weight of soil, and in many agricultural soils, <2%.

Organic matter is important for the functioning of soil in a diversity of manners:

• Chemical reservoir of slow-release nutrients;

• Physical network enabling aggregation and soil structural development;

• Biological food web to consume and assimilate metabolic energy.

As a plant growth medium, soil functions in a very important way to provide nutrients, physical support, and biological protection. As a reservoir of nutrients, soil organic matter must undergo biochemical transformations for nutrients to become available to plants [e.g. mineralization of organic nitrogen (N) to ammonium (NH_4^+) and nitrate (NO_3^-), mineralization of organic phosphorus (P) to phosphate (PO_4^{3-}), and mineralization of organic sulfur (S) to sulfate (SO_4^{2-})]. Soil organic matter contains a wide diversity of nutrients, including most of the plant-essential elements required for crop growth. Physically, soil organic matter promotes strong aggregation necessary to resist erosion by wind and water, to provide pore spaces for roots and soil organisms, and to create channels for the rapid movement of water and air through the soil profile. Biologically, soil organic matter provides the food source for a plethora of soil organisms, from macrofauna (>2 mm width x >10 mm length, e.g. beetles and earthworms) to mesofauna (0.1-2 mm width x 0.2-10 mm length, e.g. collembola and mites) to microfauna (<0.1 mm width x <0.2 mm length, e.g. protozoa and nematodes) to microflora (e.g. bacteria, actinomycetes, fungi, and algae).

Soil organic matter can be considered in a dynamic and necessary equilibrium between inputs of organic materials (e.g. crop residues, organic amendments, animal manures, etc.) and outputs in response to biochemical transformations (e.g. soil organic matter decomposition or soil respiration) and physical alterations (e.g. runoff from soil erosion and leaching from infiltration). Simply put, soil organic C stock is a function of C inputs and outputs (Fig. 1).

Decomposition is a vital ecosystem function provided primarily by soil microorganisms. Under a standard set of environmental conditions (i.e., temperature and water content), organic residues can be classified according to their decomposability. Readily decomposable residues often have high N concentration. Moderately decomposable residues may have lower N concentration or biochemically complex structural components such as polyphenols or lignin. Resistant residues will often have very low nutrient concentration and structurally complex components. In a similar manner, soil has pools of organic matter that can be characterized as active, slow, and passive (Parton *et al.*, 1987). Transformations of organic residues into soil organic matter are mediated by the activity of soil microorganisms, the entirety of which is often measured as microbial biomass (Fig. 2).

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Figure 1. Balance between carbon inputs and outputs, which determines soil organic carbon changes with time and/or management.

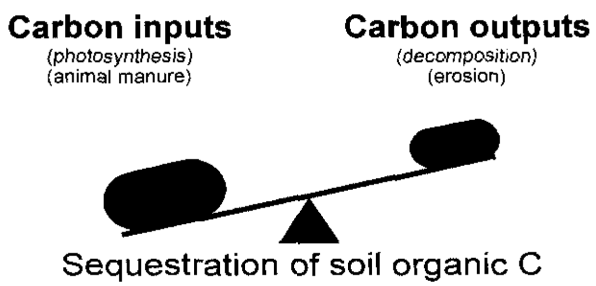

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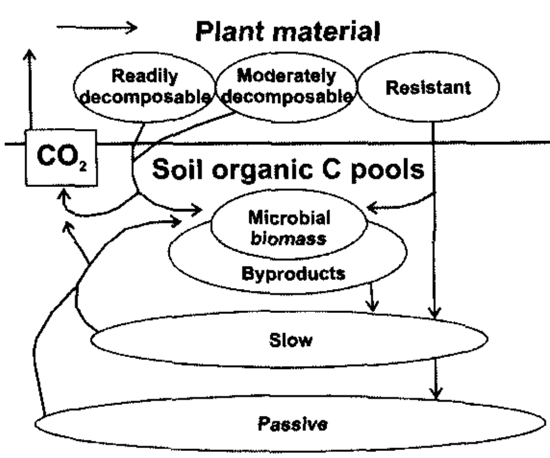
Figure 2. Pools of carbon in soil and the central role of microbial biomass in transforming organic residues into soil organic matter and releasing carbon



2. Soil organic matter depth distribution

Soil organic matter in undisturbed grasslands is typically concentrated near the soil surface (Fig. 3). Following traditional cultivation techniques of the past, organic C concentration of surface soil declines due to biochemical oxidation from frequent disturbance and physical loss with excessive erosion. As seen in Figure 3, soil organic C is also inherently dependent upon soil type, specifically of the fine fraction of soil (clay + silt). Soils with finer texture often have greater soil organic C due to binding of organic molecules to the highly reactive surfaces of clay, as well as due to the protection of organic matter within stable aggregates produced by fine particles.

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Figure 3. Soil organic carbon depth distribution under grassland and cropland in different soils of the *southeastern USA. Data from* McCracken (1959).

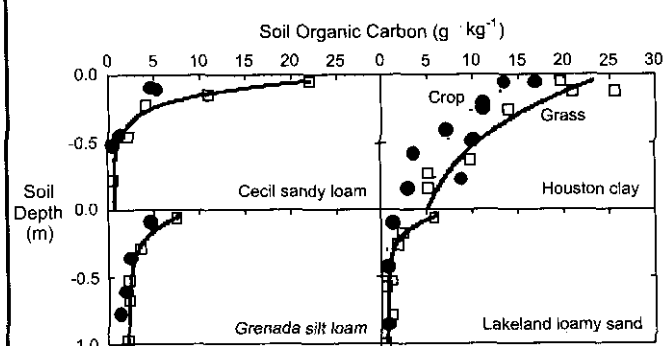


Figure 4. Depth distribution of soil organic C under conventional tillage, conservation tillage, and pasture.
Adapted from Schnabel et al. (2001).

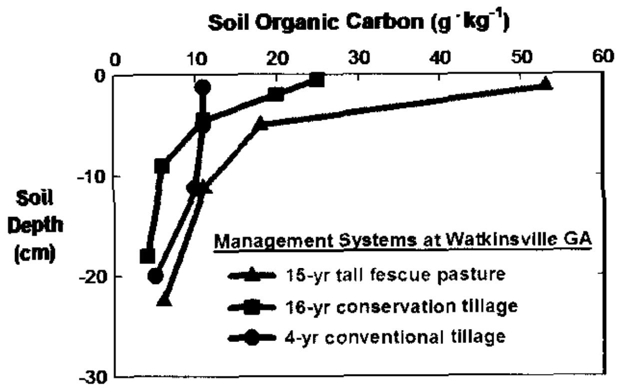
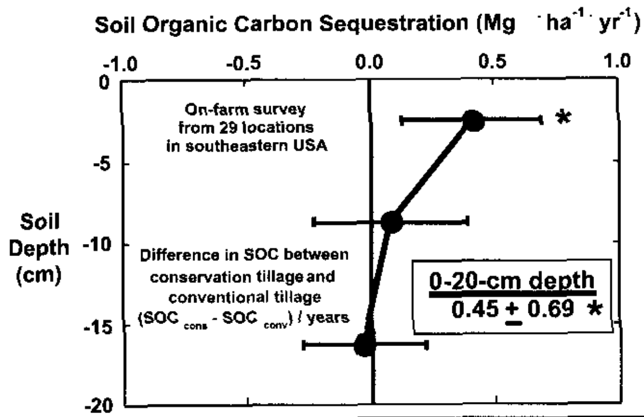
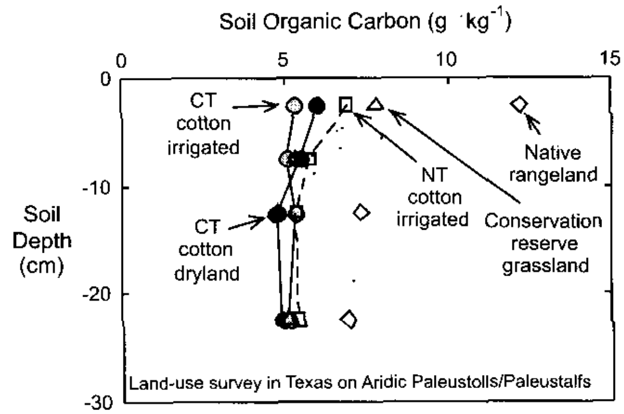


Figure 5. Soil organic carbon sequestration with conservation tillage compared with conventional tillage across 29 locations throughout the southeastern USA.
Data from Causarano et al. (2008).



Adoption of conservation agricultural systems often leads to more stratified soil organic matter with depth, in a manner more similar to native conditions (Fig. 4). Within the plow layer, soil organic C concentration following several years of NT is greater

Figure 6. Soil organic carbon concentration with depth among five land uses in western Texas.
CT is conventional tillage, NT is no tillage. Mean annula temperature was 16 °C and mean annual precipitation was 470 mm. *Data from Bronson et al. (2004).*



near the soil surface and may be lower with depth than with conventional-tillage (CT) practices.

3. Soil organic C with no tillage

Soil organic C accumulates with time under NT due to lack of soil disturbance and maintenance of a protective soil cover, both of which retard the loss of organic C often observed under CT. The rate of soil organic C accumulation with NT appears to be dependent upon a number of factors, including climatic conditions, soil type, landscape position, and type of cropping system. In the southeastern USA (a warm and wet climate; mean annual temperature of 13 to 22°C and mean annual precipitation of 900 to 1600 mm yr^{-1}), soil organic C sequestration has been estimated as 0.45 + 0.04 Mg C ha^{-1} yr^{-1} (mean + standard error, n = 147, 20 + 1 cm depth, 11 + 1 yr) with NT compared with CT cropland (Franzluebbers, 2009). This rate of soil organic C accumulation from experiment-station trials was verified in a recent on-farm evaluation of soil organic C sequestration between CT and NT cropland (Fig. 5). The relatively high rate of soil organic C sequestration in the southeastern USA contrasts with lower rates reported in the cold and dry region of western Canada

(0.32 + 0.15 Mg C ha-1 yr^{-1}) and in the cold and wet region of eastern Canada (-0.07 + 0.27 Mg C ha-1 yr^{-1}) (VandenBygaart et al., 2003). Soil organic C sequestration in dry climates is often limited by the amount of C input from plant dry matter (Fig. 6). Cold and wet climates are thought to have little stimulation of organic matter decomposition brought about by inversion tillage, thus resulting in either small actual differences in soil organic C between CT and NT or statistically insignificant effects.

Available data from the literature suggests that soil organic C sequestration with NT compared with CT does not vary greatly among soil orders. However, Franzluebbers and Steiner (2002) reported that Inceptisols had greater ($p = 0.04$) soil organic C sequestration with NT compared with CT (0.56 Mg C ha^{-1} yr^{-1}, $n = 20$) than Mollisols (0.13 Mg C ha^{-1} yr^{-1}, $n = 44$). This review of available data in North America at the time also indicated few differences in soil organic C sequestration among soil textural classes, except for greater ($p = 0.05$) soil organic C sequestration with NT compared with CT in silty clay loams (0.60 Mg C ha^{-1} yr^{-1}, $n = 18$) compared with loams (-0.02 Mg C ha^{-1} yr^{-1}, $n = 11$). Observations (Jenkinson, 1988; Amato and Ladd, 1992) and model predictions (Hassink and Whitmore, 1997) have also suggested greater potential to sequester soil organic C in soils with finer texture than coarser texture.

Landscape position can have an influence on the extent of soil organic C sequestration with NT compared with CT. In eastern Canadian soils with thin Ap horizon, NT sequestered soil organic C at a rate up to 0.8 Mg C ha-1 yr^{-1} while no sequestration occurred in moderate and thick Ap horizons (VandenBygaart *et al.*, 2002). Following a similar pattern in eastern Colorado, soil organic C sequestration with 12 years of NT was greatest in soils with initially low soil organic C (typically summit and sideslope positions) and declined to no sequestration or loss of soil organic C in soils with initially high soil organic C (typically toeslope position) (Sherrod et al., 2003). Soil organic C sequestration with NT was estimated at 0.14 Mg C ha^{-1} yr^{-1} on the summit position, 0.22 Mg C ha^{-1} yr^{-1} on the sideslope position, and -0.29 Mg C ha^{-1} yr^{-1} on the toeslope position (Sherrod et al., 2003). Loss of soil organic C with a one-time plowing of a long-term NT field in eastern Canada was only significant in a low-soil-organic-C portion of the field, but not in portions of the field with higher soil organic C (VandenBygaart and Kay, 2004).

Soil organic C sequestration with adoption of NT is often greater with more complex cropping systems. In the southeastern USA, NT cropping systems with cover cropping sequestered soil organic C at a rate of 0.53 Mg C ha^{-1} yr^{-1}, while NT cropping systems without cover cropping sequestered soil organic C at a rate of 0.28 Mg C ha^{-1} yr^{-1} (Franzluebbers, 2005). The greater input of winter biomass appears to be greatly beneficial to soil organic C sequestration in this environment. Across North America, soil organic C sequestration with NT was -0.26 Mg C ha^{-1} yr^{-1} with a cropping intensity of 0.25 (6 months of growing season per 24-month period; e.g. wheat-fallow rotation), was 0.38 Mg C ha^{-1} yr^{-1} with a cropping intensity of 0.5 (6 months of growing season per 12-month period; e.g. continuous corn), and 0.62 Mg C ha^{-1} yr^{-1} with a cropping intensity of 1.0 (12 months of growing season per 12-month period; e.g. wheat/soybean double cropping) (Franzluebbers and Steiner, 2002).

4. Soil organic C with pastures and pasture-crop rotations

The potential to store soil organic C is often much greater under managed pastures than under cropland, whether managed with CT or with NT. Soil organic C under 20-year-old tall fescue-common bermudagrass pasture was 6.7 Mg C ha^{-1} greater than under 24-year-old conservation-tillage cropland in Georgia (Franzluebbers et al., 2000). The rate of soil organic C accumulation under perennial pasture in Georgia was 1.4 Mg C ha^{-1} yr^{-1} when grazed, was 0.65 Mg C ha^{-1} yr^{-1} when left unharvested, and was 0.30 Mg C ha^{-1} yr^{-1} when hay was cut and removed (Fig. 7). These data suggest that not disturbing the soil is important for accumulation of soil organic C, but also that return of above-ground plant material either unaltered as surface residue or processed through grazing animals and returned to the soil as manure are important. These research-station results for high soil organic C sequestration with perennial pastures were verified on farms in a land-use survey throughout the southeastern USA (Fig. 8).

Rotation of crops with pastures should be considered a valuable approach towards conservation of land resources in agricultural systems, since the pasture phase can be used to rehabilitate soil organic matter while still providing economic return to producers. Pasture-crop rotation has been shown to stabilize soil organic C when using CT management during the cropping phase. On a Typic Argiudoll in Argentina, soil organic C and surface-soil structural stability to resist erosion could be sustainably managed with a maximum of 7 years of conventional

Figure 7. Soil organic carbon accumulation with time under different bermudagrass pasture management strategies on a Typic Kanhapludult in Georgia USA. *Data from Franzluebbers et al. (2001) and unpublished.*

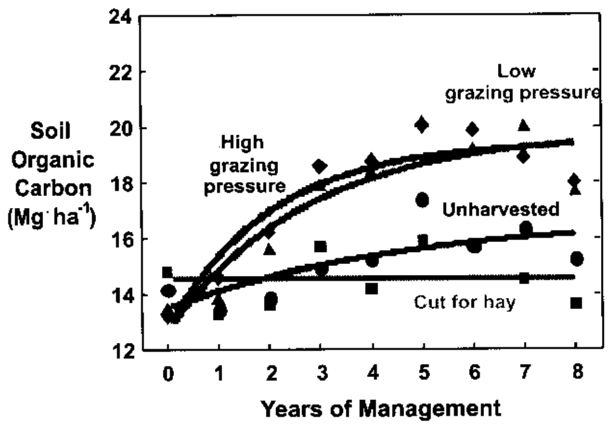


Figure 8. Soil organic carbon sequestration with pasture compared with conventional-tillage cropping across locations throughout the southeastern USA. *Data from Causarano et al. (2008).*

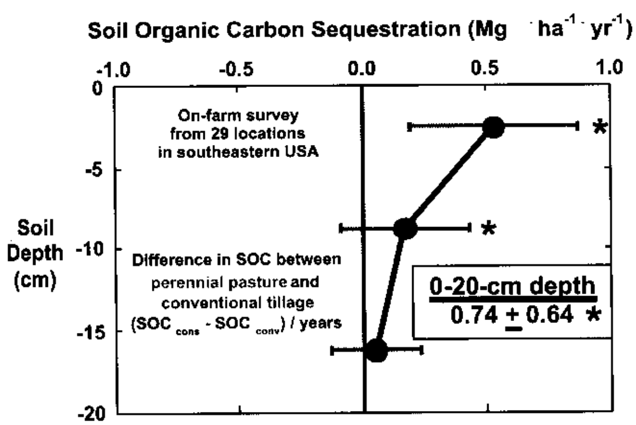
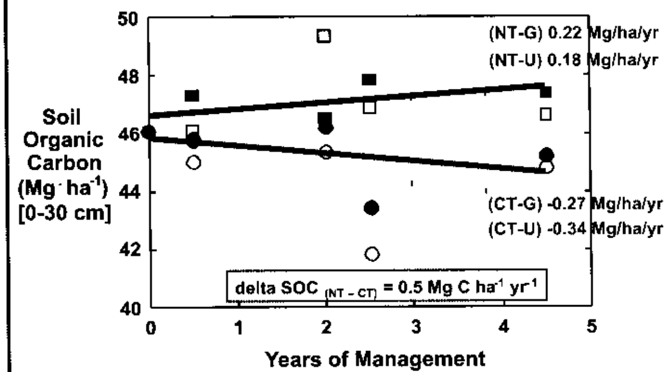


Figure 9. Soil organic carbon during the first 4.5 years of cropping following long-term pasture on a Typic Kanhapludult in Georgia USA. CT is conventional tillage, NT is no tillage, G is grazing of cover crops, and U is ungrazed cover cropping. *Data from Franzluebbers and Stuedemann (2008a) and unpublished.*



cropping rotated with a minimum of 3 years of perennial pasture (Studdert et al., 1997). Similar agro-ecosystem sustainability was demonstrated with pasture-crop rotation studies in Uruguay (Garcia-Prechac et al., 2004) and in other parts of Argentina (Diaz-Zorita et al., 2002).

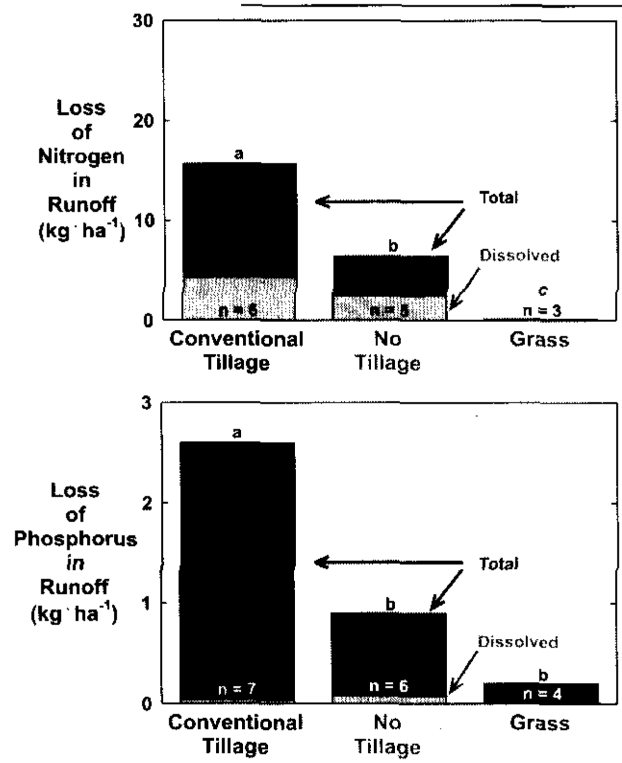
Grazing of perennial and annual pastures is often perceived as a detriment to soil organic C accumulation and sustainability of the soil resource. However, more and more evidence suggests that grazing of crop residues and annual cover crops may not be as detrimental to soil as once perceived. On a Typic Argiudoll in Argentina, soil bulk density increased with grazing of crop residues in Argentina under CT, but not under NT, suggesting that greater soil strength provided by NT can resist further compaction by animal trampling (Diaz-Zorita *et al.*, 2002). On a Typic Kanhapludult in Georgia USA, soil bulk density was little affected whether cover crops were grazed or not under NT due to the high surface-soil organic C present following rotation with perennial pasture (Franzluebbers and Stuedemann, 2008b). The rate of soil organic C sequestration during the first few years of CT and NT comparison was unaffected whether cover crops were grazed by cattle each year or not (Fig. 9).

5. Stratification of soil organic matter as an indicator of soil quality

Stratification of soil organic matter with time occurs when soils remain undisturbed from tillage (e.g. with conservation tillage and pastures) and sufficient organic materials are supplied to the soil surface (e.g. with cover crops, sod rotations, and diversified cropping systems). This stratification can be viewed as an improvement in soil quality, because several key soil functions are enhanced, including water infiltration, conservation and cycling of nutrients, and sequestration of C from the atmosphere (Franzluebbers, 2008). Stratification of soil organic C with NT generally reduces water runoff volume and soil loss from agricultural fields. Perennial pastures often reduce water runoff volume and soil loss even further than with NT cropland due to greater accumulation of surface soil organic matter. Total loss of nutrients is often lower with NT than with CT, because of a reduction in sediment-borne nutrients (Fig. 10). Dissolved P in water runoff can be a threat to water quality with excessive nutrient applications from fertilizers and manures (even under conservation management), although quantitative relationships of how dissolved P might directly affect water quality responses should be developed further.

F 10

Figure 10. Mean loss of nitrogen and phosphorus in water runoff across several water catchment studies in the USA.



Data from Van Doren et al. (1984), Langdale et al. (1985), Blevins et al. (1990), Seta et al. (1993), Sharpley and Smith (1994), Shipitalo and Edwards (1998), Endale et al. (2000, 2001, 2004), Ross et al. (2001), Rhoton et al. (2002), Sharpley and Kleinman (2003), Truman et al. (2003), Harmel et al. (2004), and Bosch et al. (2005).

Stratification ratio of soil organic C has been proposed as an index of soil quality, because soil-surface enrichment of organic matter is important for improving water-stable aggregation, water infiltration and storage, nutrient cycling, and soil microbial biomass, activity, and diversity (Franzluebbers, 2002).

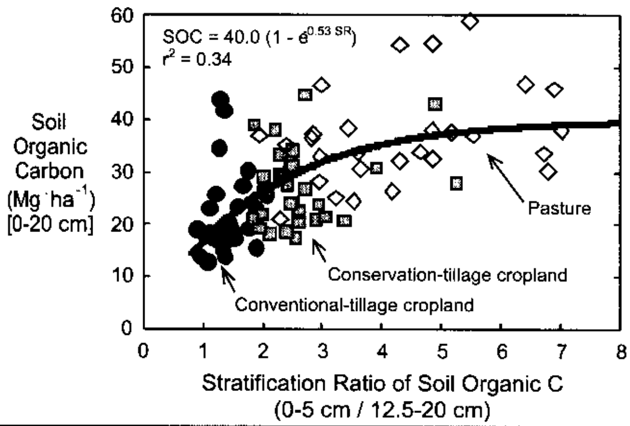
In a survey of agricultural land uses in Alabama, Georgia, South Carolina, North Carolina, and Virginia, stratification ratio of soil organic C (0-5 cm / 12.5-20 cm) averaged 1.4 with CT cropland and reached a plateau of 2.8 within 10 yr of NT cropland and a plateau of 4.2 with perennial pasture. In a survey of cropland fields on three different soil types in the Virginia Coastal Plain, stratification ratio of soil organic C (0-2.5 cm / 7.5-15 cm) was linearly related to the number of years of continuous NT (initially 1.5 following conventional tillage and increasing to 3.6 with 14 years of NT) (Spargo *et al.*, 2008).

Stratification of soil organic C with depth may be predictive of terrestrial C storage with conservation agricultural systems in the southeastern USA. In the land-use survey by Causarano et al. (2008), stratification ratio of soil organic C was related to the total stock of soil organic C in the surface 20-cm depth (Fig. 11). This relationship indicates that the majority of C stored with conservation management in these Ultisols and Alfisols of the region occurred within the surface 5 cm. More data will be needed to extend the applicability of this relationship throughout the region and beyond. When using only the surface 2.5 cm of soil for calculation of the stratification ratio, there was little relationship between stratification ratio and the stock of soil organic C in the surface 15 cm of conservation-tilled Coastal Plain soils in Virginia (Spargo et al., 2008). Taking these data together suggests that significant accumulation (if not the majority) of soil organic C occurs within the surface 5 cm with conservation management.

F 11

Figure 11. Relationship of soil organic carbon storage at a depth of 0-20 cm to the stratification ratio of soil organic carbon among conventional-tillage, conservation-tillage, and pasture land uses on different soils throughout the southeastern USA.

Data from Causarano et al. (2008).



6. Summary and conclusions

Soil organic matter is an essential component of high quality soil. Organic matter is often enriched at the soil surface with conservation agricultural management. Both NT and pasture-crop rotations can help build and maintain soil organic matter. Highly stratified soil organic matter with depth is indicative of soils' ability to preserve environmental quality, particular through water quality abatement and sequestration of atmospheric C into soil organic C.

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